A simulator evaluation of effects of assistive technologies on driver cognitive load at railway level crossings

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Abstract
Intelligent Transport Systems (ITS) have the potential to substantially reduce the number of crashes caused by human errors at railway levels crossings. However, such systems could overwhelm drivers, generate different types of driver errors and have negative effects on safety at level crossing. The literature shows an increasing interest for new ITS for increasing driver situational awareness at level crossings, as well as evaluations of such new systems on compliance. To our knowledge, the potential negative effects of such technologies have not been comprehensively evaluated yet. This study aimed at assessing the effect of different ITS interventions, designed to enhance driver behaviour at railway crossings, on driver's cognitive loads. Fifty eight participants took part in a driving simulator study in which three ITS devices were tested: an in-vehicle visual ITS, an in-vehicle audio ITS, and an on-road valet system. Driver cognitive load was objectively and subjectively assessed for each ITS intervention. Objective data were collected from a heart rate monitor and an eye tracker, while subjective data was collected with the NASA-TLX questionnaire. Overall, results indicated that the three trialled technologies did not result in significant changes in cognitive load while approaching crossings.
Keywords
Intelligent Transport Systems (ITS); Driving simulator; Railway level crossings (RLX); Driver cognitive load

1. Introduction

Level crossing crashes result in enormous human and financial cost to society. "Level crossings are the single greatest source of risk to safety on the rail network" (CRC for Rail Innovation, 2010). Most analyses have demonstrated that errors and violations on the part of the road user are the largest contributor to level crossing crashes and near miss incidents (Australian Transport Safety Bureau, 2002; Edquist, Stephan, & Wigglesworth, 2009), indicating the urgent need for innovative road-based interventions to complement railway interventions. Innovative road based interventions directly targeting driver behaviour are highly promising approaches to improve railway level crossing safety. Indeed, in recent years there has been a rapid growth in the development of a variety of emerging technologies in the area of railway level crossing safety (State of Victoria, 2009; Tey, Ferreira, & Dia, 2009). A review of the literature has shown that safety at both passive and active Railway Level Crossings (RLXs) could be improved by Intelligent Transport Systems (ITS) interventions, and that ITS should focus on providing drivers with simple, easy to process information about the approach of trains (Buckley, Larue, Haworth, & Rakotonirainy, 2013). It is hypothesised that ITS technologies for level crossing protection systems will reduce the occurrence of crashes which would, in turn, reduce their associated cost and negative impacts on the economy in terms of value of loss of life, lost productivity and delays. Various studies have trialled new interventions for level crossings (Larue et al., 2014; Lenné et al., 2011; Tey, Wallis, Cloete, Ferreira, & Zhu, 2012), but focusing primarily on the expected positive effects of increasing driver awareness at crossing using new ITS technologies. However, such interventions could also potentially have negative effects, particularly related to mental cognitive load, distraction and over-reliance. The aim of this study is to evaluate whether three different ITS interventions (in-vehicle and on road) could result in excessive driver cognitive load that would impair their driving performance. This will contribute to a better understanding of the potential human factor issues of the different ITS systems that are likely to be implemented at railway level crossings.

2. Background

Mental or cognitive workload is a specification of the capacity an operator spends on task performance. During information processing, attention resources are limited and divided between the different tasks needed to perform and the stages of information processing (Pashler, 1998; Wickens & Hollands, 2000). During controlled processing, task performance increases quickly but also reaches a threshold rapidly (Eysenck, 2005). The complexity of the task is a known factor influencing directly the level of performance when performing the task. In the case of two demanding tasks, one task or the other suffers from this limitation of resources (Wickens, 2002). Driving is a visual task requiring high cognitive load from the driver. It is therefore necessary to ensure that additional tasks do not result in a large increase in cognitive load, particularly for interventions targeting difficult driving situations where the driver cannot respond to the situation on their own. Driving being a visual task, it is particularly important to assess cognitive load for new information conveyed by visual displays.

Driver cognitive load refers to the amount of effort a driver devotes to the driving task. It has also been defined in general as a set of task demands, as effort, and as activity or accomplishment (Gartner & Murphy, 1979), where the task demands are the goal to be achieved, including the time allowed to perform the task, and the performance level to which the task is to be completed (Gawron, 2008). Workload is a multidimensional construct involving interactions between the task and system demands, the operator (including mental and emotional capabilities) and the environment (Sanders, 1979; Schlegel, 1993). In the driving context, workload is commonly defined as the effort required to maintain the driving state within a subjective safety zone (Boer, 2005). In transportation research, driver workload can also refer to the amount of effort a driver devotes to the driving task.

There are four methods which can be used to measure driver cognitive load (Gawron, 2008):

- secondary task performance
- subjective estimates of workload (NASA-TLX)
- physiological measures (cardiac activity)
- stand-alone performance measures (such as driver eye glance behaviour for a stand-alone performance measure of the visual workload).

Secondary task performance is one of the most commonly used measures of workload in driving research. Implementing a secondary task is not an appropriate solution for assessing workload in this experiment as this study aims to create a driving task as close to reality as possible.

Subjective estimates of driver workload are usually comprised of one or more questions presented in a questionnaire format which are designed to probe a driver's experience of workload. One of the most commonly used subjective workload questionnaires used in driving research is the NASA Task Load Index, or NASA-TLX (Hart & Staveland, 1987). The NASA TLX is a multidimensional rating instrument that assesses six dimensions of subjective workload: mental demand, physical demand, temporal demand, performance, effort, and frustration level. Participants are required to indicate their subjective experience of workload in each of these six categories by indicating a point on a graded scale. There are also subjective workload measurement scales which have been specifically designed to assess driver workload. For example, the Driving Activity Load Index (DALI) is a modified version of the NASA TLX which has been specifically tailored to the assessment of in-vehicle systems and tasks in the automotive environment (Pauzié, Manzan, & Dapzol, 2007). This method has nevertheless not been used in an extensive manner that would ensure of its reliability.

Physiological measures are also used in driving research to assess mental workload. For example, cardiac activity (heart period, HR and, to a lesser degree, heart rate variability HRV) has been found to be related to the amount of workload experienced by a subject (Cinaz, Arnrich, La Marca, & Tröster, 2011).

Heart beats have varying time durations, resulting in inter-beat intervals (IBI) time series with characteristic patterns and frequency contents (Stanton, Hedge, Brookhuis, Salas, & Hendrick, 2004) (Stanton et al.). Most studies show that the metric heart rate, if it changes at all, increases and the metric heart rate variability decreases during increased mental processing (Ahsberg, Gamberale, & Gustafsson, 2000; Oron-Gilad, Ronen, & Shinar, 2008), though contradictory results have been found.

A clear increase in HR and decrease in HRV were found with increased workload in an on-road study (Brookhuis, de Vries, & de Waard, 1991) examining the effects of mobile phone conversations on driving performance. A simulator study was conducted which collected HR and HRV data (in conjunction with the NASA-TLX and the Peripheral Detection Task) to measure the workload demands of interacting with two route guidance systems while driving. HR and, to a lesser degree, HRV (due to high inter-individual variability) were sensitive to the workload manipulations in the driving study, with increased workload causing increases in HR (Jahn, Oehme, Krems, & Gelau, 2005).

An example of a stand-alone performance measure of the visual component of driver workload is driver eye glance behaviour. In particular, increased glance duration and greater frequency of glances to a particular area in a driver's visual field are generally accepted as measures of increased visual workload (Gawron, 2008).

Three out of the four methods were implemented in order to get a comprehensive evaluation of workload with the different ITS interventions: NASA-TLX, physiological measures and eye glance behaviour.

3. Method

3.1 *Participants*

A sample size of $N = 60$ was expected to yield adequate statistical power for detecting between-group differences with 80% power (Kirkwood & Sterne, 2003). A total of 76 participants, were recruited to take part in the study. Eighteen participants were unable to complete the study due to motion sickness and technical errors, and were thus excluded from final analyses. The final sample consisted of 58 drivers, 39 (67%) males and 19 (33%) females, aged 19 to 59 years ($M = 28.2$, $SD = 7.63$). The three groups of participants were balanced in terms of gender, exposure to railway crossings, (with 'regular experience' of driving at crossings being defined as driving across RLXs at least once a week), age and driving experience. A total of 20 participants were allocated to trial the visual in-vehicle ITS; 19 were allocated to the audio in-vehicle ITS condition and; 19 trialled the on-road valet system. The allocation of participants to a group was done with a simple random sampling.

Participants were recruited via advertisements placed in Brisbane local newspapers, Queensland University of Technology's psychology undergraduate research participant pool, and snowballing methods. To be eligible for participation, participants were required to have held a drivers licence for at least two years and drive more than 10,000km per year (classing them as regular drivers). Potential participants were screened to ensure that they did not suffer from epilepsy, motion sickness, or pre-existing medical conditions or injuries involving the back and neck that would compromise their ability to use a driving simulator. Participants' written consent was obtained prior to data collection. Participants received a $50 incentive for participating in the study. This study had ethical clearance from the ethics committee.

3.2 Equipment

3.2.1 Advanced Driving Simulator

The ITS devices tested in the current study were implemented using the CARRS-Q Advanced Driving Simulator (see Figure 1). The simulator included a complete automatic Holden Commodore vehicle with working controls and instruments, and used SCANeR™ studio software with eight computers, three projectors and a six degree of freedom motion platform. When seated in the simulator vehicle, the driver was immersed in a virtual environment which included a 180 degree front field view composed of three screens, simulated rear view mirror images on LCD screens, surround sound for engine and environment noise, real car cabin and simulated vehicle motion. The road and surrounding environment were designed to represent, as closely as possible, realistic traffic conditions developed in accordance with Australian Standards at railway crossings. The simulator was also equipped with a Facelab version 5 eye tracker.

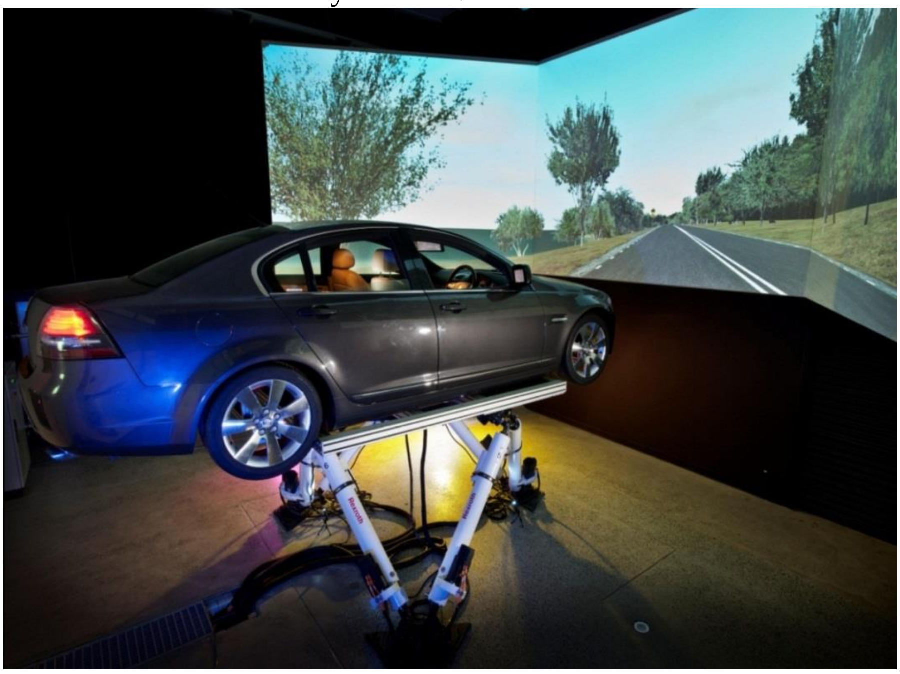

Figure 1: CARRS-Q Advanced Driving Simulator

3.2.2 The three ITS devices

All three devices trialled in the current study provided similar information through different human machine interfaces. Each device served to provide the driver with two primary safety messages: 1) the reason for the warning to be displayed (a train was approaching the crossing), and; 2) the action the driver was expected to perform (i.e., to stop rather than proceed at the crossing).

3.2.2.1 Visual ITS

The visual in-vehicle ITS device was implemented using a Nokia smartphone. RTmaps (www.intempora.com/) was used to collect information directly from the driving simulator and generate real-time messages on the in-vehicle device. The device was positioned within the driving cabin at the usual, centre-dashboard location of a GPS.

In the “train approaching” scenario, and at active crossings, the device displayed two alternative pictures (see Figure 2) which mimicked the flashing light effect seen at active crossings. For passive crossings, the warning was displayed at the time the crossing would have been activated if the crossing was actively protected. The warning conveyed both explanation and action messages to the driver in one symbolic representation, indicating that a train was approaching the crossing and that the driver was expected to stop.

Figure 2: Symbolic representation of the visual human machine interface – Train approaching case. (The lights are flashing in red)

3.2.2.2 Audio ITS

The audio in-vehicle ITS device was implemented using the existing vehicle manufacturer installed speakers inside the car (door mounted) to provide verbal warning messages to the driver. Through simulator scripting the messages were played as the status of the crossing changed and required a particular warning. In the “train approaching” scenario, a verbal warning was provided whilst the flashing lights of simulated active crossings were activated. For passive crossings, the warning was provided at the time the signal would have been activated if the crossing was actively protected (25 seconds before the train would reach the crossing). Similar to the two messages provided in the visual ITS, the verbal warnings were “*Train approaching the crossing ahead*” and “*Stop at the crossing*”.

3.2.2.3 On-road flashing markers

The road-based ITS system used flashing warning beacons on the road which were activated when a train was approaching the crossing. These beacons highlighted, in a similar way as illuminated airplane runways, the location where the driver was expected to stop their vehicle. Such an intervention is similar to the SafeZone system (valet) from Inventis Technology. In the current study, flashing markers on the road were activated at the same time as the flashing lights of an active crossing, and were positioned up to 150 metres from the crossing, which is the location where signs are located for passive crossings in Australia with speed limits of 60 kilometres per hour, as specified in the Australian standard (Standards Australia, 2009). In the case of passive crossings, the lights were activated 20 seconds prior to the arrival of the train, providing a comparable time for the driver to react to the warning. Three in-road red lights were used to emphasise the stop line at the crossing. Five in-road yellow lights were positioned in the middle of the road every 6 metres, and a further ten yellow lights were positioned every 12 metres. Each individual flashing beacon was designed in accordance with Australian Standards reflective road markers.

With a train approaching, the ITS was activated via scripting similar to that used to generate messages regarding the flashing lights of an active crossing. Because of the nature of the valet system, the reason for road markings to flash (primary message 1) was not communicated via the ITS itself but was instead conveyed to the participant during training to ensure that they understood the ITS message. Figure 3 provides a screen capture of the simulated road markings from the driver's view.

Figure 3: Simulator rendering of the on-road ITS

3.3 Measures

The level of mental load was subjectively assessed by participants using a scale between 0 and 20. Heart rate monitoring was used as a complement of the driving simulator as a way to objectively assess whether the ITS intervention had an effect on the workload of participants. It has been shown that with higher mental processing, heart rate tends to increase, while heart rate variability (variability of the interbeat intervals) tends to decrease.

Eye gaze pattern was measured as the time spent looking at the road or particular signs in the road environment, as well as the time spent looking at the visual ITS.

3.3.1 Procedure

Upon arrival, participants completed a questionnaire assessing their demographics, general driving experience and exposure to passive and active crossings. Participants were then provided with a familiarisation drive in the driving simulator allowing them to become accustomed to accelerating, stopping, and driving though intersections, active and passive railway crossings and curves, as well as the road environment, composed of both urban and rural sections (see Figure 4).

Each participant took part in a simulated driving task consisting of three scenarios, each taking approximately 15 minutes to drive. Between each scenario, participants were taking 10 minutes breaks.

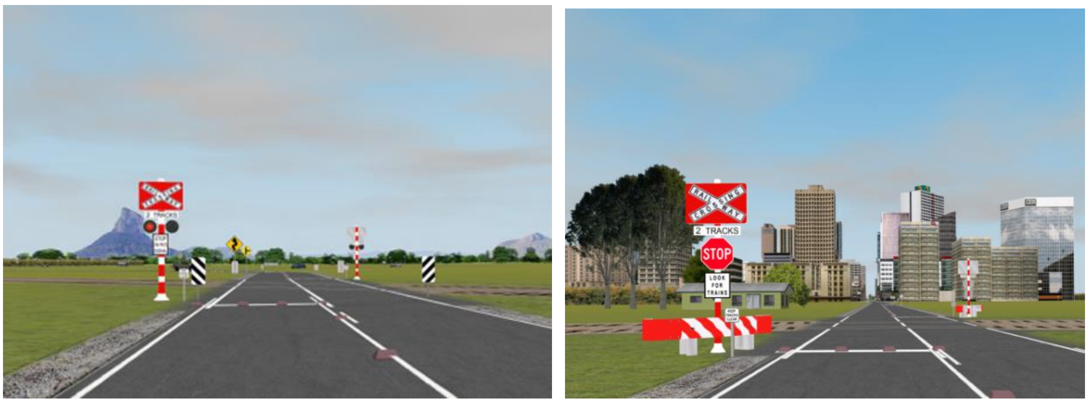

Figure 4: Simulated road environment

Prior to their practice drive with the ITS intervention, participants were briefly exposed to the ITS system to which they were allocated. For both the visual in-vehicle ITS and road-based valet conditions, participants were presented with paper-based screen captures from the simulator and photos of the device from inside the vehicle. In the case of the audio ITS, verbal messages were played to the participant. Participants were then given a familiarisation drive with the ITS switched on to enable them to feel confident whilst driving with the system activated. Participants subsequently drove two driving scenarios, each containing the same number of traffic lights, intersections and active and passive crossings, but differing in terms of the order in which they were presented. Each scenario had eight level crossings- half passive, half active – and three of these crossings had trains approaching as participants arrived at the crossing. The trains were programmed to be at the location of activation of the level crossing 4 to 6 seconds before the participants arrived at the crossing stop line. This setting ensures drivers have to take a decision as they arrive at the crossing. It has to be noted that such setting is unlikely to result in crashes, as drivers have enough time to process the information and brake to a complete stop, or proceed through the crossing before the train arrives. Effects of the ITS interventions are therefore evaluated on surrogate measures. Each participant randomly drove one of the scenarios with the system turned off and the other one with the system activated, lasting approximately 30 minutes in total. The order of scenarios was randomly assigned to the participants as they arrived at the driving laboratory. Ten minute breaks were provided between scenarios, during which time participants completed the NASA-TLX questionnaire. The total session time did not exceed 2 hours.

4. Results

4.1 NASA-TLX

A Generalised Linear Mixed Model (GLMM) analysis of the NASA-TLX data was used to take into account the repeated measures of the study design. This analysis shows that mental load is similar for the three trialled ITS when compared to the baseline without any ITS intervention. The reported value of mental demand by participants is 8.05 with a standard deviation (SD) of .70.

Similar analysis was conducted for drivers effort (7.6 with a standard deviation of .65), frustration (6.4 with a standard deviation of .65) and performance (15.9 with a standard deviation of .37), and resulted in similar outcomes as with mental demands: no differences were observed with the ITS interventions.

GLMM analysis was conducted for physical demands subscale of NASA-TLX and resulted no statistical difference for the audio and valet interventions, with a reported value of 6.1 (standard deviation of .59). The visual in-vehicle ITS resulted in higher physical demands which were on average 1.8 points higher on the scale ($t=2.54$, $df=111$, $p=.013$), reaching 7.9 ($SD=.86$).

For temporal demands subscale of NASA-TLX , the audio in-vehicle intervention was similar to the baseline, with a value of 7.0 ($SD=.61$). The visual in-vehicle ITS resulted in an increase by 1.4 of temporal demands ($t=2.22$, $df=111$, $p=.029$), while the valet intervention resulted in a reduction of temporal demands by 1.7 ($t=-2.72$, $df=111$, $p=.008$).

4.2 Physiological measures

Heart rate was extracted from the raw HR data and heart rate variability was extracted from the interbeat interval values. No difference was observed for both heart rate and heart rate variability. Average heart rate of 74.9 beats per minute (SD) was recorded, while heart rate variability was 0.20 (SD). This suggests that there is no increase in mental processing when approaching passive crossings with these interventions.

The same results were obtained for active crossings for the visual in-vehicle intervention and the valet interventions. Differences were observed for the audio in-vehicle intervention.

Heart rate is 74.9 beats per minute on average in the baseline scenario (see Table 1). With the audio ITS, the heart rate reduces by 2.3 beats per minute to 72.6 (t=-1.99, df=34, p=.054). This result is at the limit of statistical significance. If the audio ITS has any noticeable effect on workload, it is in a positive manner by reducing it, as heart rate is likely to slightly diminish.

Table 1: Heart rate with and without the audio ITS

ITS	**High visibility**		**Low visibility**	
	Heart rate	**SD**	**Heart rate**	**SD**
No ITS	74.9	0.61	74.9	0.61
Audio			72.6	1.00

Heart rate variability depends on the type of ITS, RLX visibility and their interaction. This provides the results presented in Table 2. The differences between all these conditions are statistically significant with p-values between .020 and .039. While heart rate variability reduces with ITS for high visibility crossings, it increases with low visibility crossings. This suggests positive effects for the low visibility crossing and negative effects for high visibility crossings. This could be due to the fact that the audio ITS helps when visibility is reduced, while the ITS provides redundant information when the visibility is high.

Table 2: Heart rate variability with and without the audio ITS

ITS	**High visibility**		**Low visibility**	
	Heart rate variability	**SD**	**Heart rate variability**	**SD**
No ITS	0.207	0.005	0.191	0.005
Audio	0.188	0.005	0.207	0.005

4.3 Eye glance behaviour

When approaching the railway crossing, participants did not change their gaze patterns towards road signage about the crossing with any of the three ITS interventions. While time spent on signage depends on various factors of the crossing, no differences were observed with the use of technology. In particular, these times were observed to slightly increase for low visibility crossings by 0.18 seconds (t=-3.78, df=257, p=<.001), decrease at passive crossings by 0.17 seconds (t=-4.18, df=257, p=<.001), and increase when a train was approaching the crossing by 1.71 seconds (t=5.19, df=257, p=<.001).

For the case of the visual in-vehicle intervention, we also assessed the time spent looking at the smartphone in the vehicle. During the baseline, drivers did not glance over this part of the dashboard. After installing the in-vehicle ITS, participants spent on average .64 seconds (t=4.07, df=138, p=<.001) looking at the GPS when approaching a crossing without a train, and .91 seconds (t=2.03, df=138, p=.043) when a train was approaching the crossing. Such times suggest that drivers were not spending high amounts of time looking at the display while approaching crossings.

5. Limitations

This study has been conducted in a driving simulator. While such methodology can predict the likely effects of new interventions, on-road experiments are still necessary to ensure the reliability of such results.

We had a relatively small number of participants. While it is statistically sufficient for determining the effects on our cohort of participants, it is not enough to estimate whether such results can be generalised to the wider Australian driving population. In particular, it would be necessary to know how groups of drivers more likely to suffer from high cognitive load while driving cope with these interventions (e.g. novice and older drivers).

The three trialled ITS interventions were trialled on their own. It would be necessary to evaluate the effects of the in-vehicle interventions when they are linked with other warning interventions for other road hazards. Indeed, having ITS capabilities in cars is likely to result in a lot of different applications for road safety issues, potentially resulting in confusing or cognitively challenging systems to use for drivers. The in-vehicle interventions tested in this study should in particular be tested when they are integrated within an existing GPS navigation device. Also, any changes to the Human Machine Interface of such interventions should be evaluated.

6. Discussion

Overall the three different ITS interventions do not generate unreasonable workload for the driver. No participant experienced crashes at the level crossing, with or without the assistive systems. A few differences were reported by drivers for the phone and valet ITS interventions, compared to the baseline. Physical demand is slightly higher for the visual in-vehicle intervention, with an increase of 1.8 on a 21 point scale. Such an increment could be due to the fact that the driver has to intentionally look towards the device, while such movement is not required for other ITS interventions (on road or audio) or during the baseline. While obtaining the information is more demanding for the phone intervention, its value is still fairly small and should not be an issue if such ITS intervention was implemented, particularly since no other differences were observed for the visual in-vehicle intervention from the objective evaluation of workload .

Temporal demand depends on the type of ITS. While the in-vehicle audio intervention did not change the temporal demand compared to baseline, the visual ITS in the car increased it and the valet system decreased it. The order of magnitude of this change is around 1.5 on the scale. Such a difference should not be an issue for the phone intervention, but this result suggests that participants feel more comfortable with an intervention directly on the road or an audio intervention rather than an intervention that requires them to modify their visual activity.

Participants' cognitive load was largely unchanged with the trialled technologies. An objective difference was found for the audio intervention at active crossings, with a positive effect for crossings with low visibility and negative effects for high visibility crossings. This could be due to the fact that the audio ITS helps when visibility is reduced, while the ITS provides redundant information when the visibility is high. The results from both subjective and objective measures are largely consistent, and suggest that these interventions are not likely to result in high cognitive load for drivers. Eye gaze behaviour towards the road signage at crossing was also shown to be unchanged with any of the three technologies. Further, the visual in-vehicle intervention did not require participants to spend dangerous amounts of time looking at the display to extract the relevant information to take the appropriate decision at railway crossings.

Participants reported slightly higher demands with the visual in-vehicle intervention, and lower demands with the audio in-vehicle ITS and the on-road valet ITS. This suggests that interventions that ensure drivers can keep their eyes on the road and on the rail track looking for trains while approaching a railway crossing, are interventions more likely to have reduced effects on driver behaviour during approach, and hence reduced opportunity for overloading the driver.

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